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HOLOCENE FAULTING AND LIQUEFACTION ALONG THE SOUTHERN
MARGIN OF THE NORTH AMERICAN CRATON (ALABAMA-OKLAHOMA
TRANSFORM)

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ABSTRACT

   The New Madrid seismic zone of the central United States has been the site of some of the largest historic earthquakes in an intraplate setting, and it produces large earthquakes because it occupies a deep-seated basement fault system (the Reelfoot rift) that is a significant discontinuity in the North American plate interior. However extensive seismically-generated sand blow fields in southern Arkansas and northern Louisiana overlie a more substantial crustal discontinuity. Gravity modeling and deep seismic refraction/reflection profiling of the Gulf of Mexico coastal plain in that region shows an abrupt transform fault margin of the North American craton that formed during breakup of Rodinia in early Cambrian (Alabama-Oklahoma transform). It strikes southeast, buried beneath the late Paleozoic Ouachita thrust sheets and overlying Mesozoic/ Cenozoic sediments. During the Ouachita orogeny, thrust sheets conformed to this edge of the craton. Deep reflection profiles for petroleum exploration show that during initial Triassic opening of the Gulf of Mexico, the crust rifted again along this deep, sub-thrust sheet discontinuity and formed a southeast-striking a graben system with > 1 km of structural relief (Saline River fault zone, SRFZ). On reflection profiles, some of these graben faults show post-Triassic reactivation with flower structure geometries having both positive and negative elements and up-dip changes in sense of separation (suggesting a strong strike-slip component). Some SRFZ faults cut the Cenozoic section. Previous excavations of surface exposures of the SRFZ in Monticello, Arkansas show displacement and deformation during Eocene, Pleistocene, and Holocene where shallow faults in these Triassic grabens should reach the surface.

   In this study, five additional sites along the SRFZ in south Arkansas were investigated. At Horsehead Island on the southern margin of the SRFZ, a down-to-the-northeast surface fault rupture diverted the Saline River 2 km to the margin of its floodplain circa 1900-1400 yr B.P. Across a graben from Horsehead Island, a trench across a linear scarp at Gee's Landing revealed three paleoearthquakes at 13,400-7700 yr B.P., 1400-1300 yr B.P., and 1200-1050 yr B.P. on a steep down-to-the-southwest fault. Near Rison in the northern SRFZ, a faulted anticline (down-to-the-southwest) post-dates alluvium that yields ^{14}C ages of 790-550 yr B.P. Thirteen kilometers southeast of the Rison anticline at Vince Bluff, another anticline with no topographic scarp folds alluvium that yields ^{14}C ages of 5893-5804 yr B.P. and 5775-5642 yr B.P. Last, a trench in Mid/Late Holocene alluvium (~6000-3000 yr B.P.) at Boydell revealed no faulting within 2 m of the surface, although shallow geophysics and coring indicate near surface faults at this site.

   These results can accommodate a 70 km rupture along a central fault of the northern graben of the SRFZ circa 6000-5000 yr B.P. Mid-Holocene sand blows in the region may record such a fault rupture, but much more data is required to make meaningful correlations between fault rupture ages and sand blow ages.

INTRODUCTION

The distribution of seismogenic faults is not well understood in the central United States beyond the immediate vicinity of the New Madrid seismic zone (NMSZ). The NMSZ has been the site of some of the largest historic earthquakes in an intraplate setting (Nuttli and Brill, 1981; Johnston, 1989; Johnston and Schweig, 1996) because it occupies a deep-seated basement fault system (the Reelfoot rift) that is a significant discontinuity in the North American plate interior (Ervin and McGinnis, 1975; Kane et al., 1981; Dart, 1995; Schweig and Van Arsdale, 1996; Braile et al., 1997). However, widespread Quaternary and Holocene faulting and seismically-induced liquefaction to the south of the NMSZ in south Arkansas and north Louisiana on the Gulf of Mexico coastal plain overlie a more substantial lower-crustal discontinuity. This young deformation follows the northwest-striking Alabama-Oklahoma transform fault (the rifted edge of the North American Proterozoic cratonic basement)(Thomas, 2006), expressed at the surface as the Saline River fault zone (SRFZ)(Cox et al., 2000; 2004a; 2004b; 2007).

Quaternary displacement on the SRFZ is dominantly left-lateral, with both normal and reverse components (Cox et al., 2000; 2004b). At one trench site (Cox et al., 2000), a fault of the SRFZ has 30 m of left-lateral offset that post-dates late Wisconsinan-age Peoria loess (23,600±3000 ka), indicating an average slip rate between 1.0 mm/y and 1.5 mm/y on this branch of the SRFZ since late Wisconsin. The Meers fault of the Southern Oklahoma Rift is another active element of the system of transform faults containing the Alabama-Oklahoma transform (Thomas, 2006), and a similarity in northwest strike and left sense of Holocene slip between the SRFZ and the Meers fault (Donovan et al., 1983; Luza et al., 1987; Ramelli and Slemmons, 1990) suggests that within the contemporary northeast-southwest compressive stress field of the midcontinent (Zoback, 1992), faults associated with favorably oriented lower-crustal discontinuities may present seismic hazards over a much larger area than the NMSZ alone. Indeed, a recent magnitude 6 earthquake on September 10, 2006 on a northwest-striking reverse fault in the north-central Gulf of Mexico (26.4N, 86.5W) attests to ongoing northeast-southwest compression throughout the southern part of the North American plate.

Geologic and Tectonic Framework

The study area is on the northern Gulf of Mexico coastal plain, an Atlantic-type passive margin that began with Triassic rifting during Pangean breakup. Within the proposed study area, 2 km of Mesozoic/Cenozoic sediment overlie rifted Paleozoic basement (Murray, 1961; Cushing et al., 1964; Salvador, 1991; Hosman, 1996). Initial rifting and graben development during Mesozoic was aligned with a zone of lower-crustal weakness along the late Proterozoic Alabama-Oklahoma transform fault on the southern edge of the craton (Fig. 1)(Sawyer et al., 1991; Thomas, 2006). Geophysical modeling of this deep Proterozoic cratonic margin show it to be a sharp discontinuity (not typical of an extended transitional crust) and supports a transform fault interpretation (Mickus and Keller, 1992; Harry and Londono, 2004). Preceding Triassic rifting, thrust sheets were emplaced obliquely over the late Proterozoic Alabama-Oklahoma transform margin during the late Paleozoic Ouachita orogeny, and the transform experienced strong right-lateral transpression (Hale-Erlich and Coleman, 1993).

The study area is north of the up-dip limit of a salt horizon near the base of the Gulf sedimentary sequence, and so salt tectonics have not played a role there. Although

the primary style of deformation south of the study area on the northern Gulf Coast is salt tectonism, there are also en echelon fault and fold arrays, laterally offset isopach trends, vertical faults with flower structure geometries on seismic reflection profiles, and other lines of evidence that reveal episodes of contractional basement deformation from Jurassic to late Cenozoic, primarily strike-slip faulting (Fowler, 1964; Turner and Fielder, 1985; Zimmerman, 1995; Fillon et al., 1999; Turner, 2001).

Three proprietary petroleum industry deep seismic reflection profiles used for this study reveal a northwest-striking Triassic graben system with ~1 km of structural relief that is coincident with the SRFZ. Initial relief was greater, but topographic highs of this rift terrain were subject to erosion for a significant period (as much as 30 m.y.), and Upper Triassic to Lower Jurassic terrigenous clastics and volcanics (230 to 195 Ma) were deposited in these rift grabens over Paleozoic sedimentary "basement" (Imlay, 1949; Salvador, 1991). This rift environment was followed by widespread marine transgression and deposition beginning in Upper Jurassic, but the Upper Jurassic and Lower Cretaceous part of the sequence was stripped from the study area during mid-Cretaceous uplift and erosion (Imlay, 1949; Salvador, 1991; Cox and VanArsdale, 2002).

During the South Arkansas Uplift/mid-Cretaceous Igneous event (100 to 90 Ma), the study area was broadly uplifted and eroded (Bornhauser, 1958; Ewing, 1991; Salvador, 1991; Cox and VanArsdale, 2002), and the Monroe Uplift (terminated on its northeast flank by the SRFZ) experienced accentuated uplift and erosion during this epeirogenic event and again later from 80 to 70 Ma (Ewing, 1991; Sohl et al., 1991). The mid-Cretaceous erosional unconformity is buried by conglomeratic clastics (95 to 90 Ma), and Late Cretaceous (88 to 65 Ma) was marked by punctuated subsidence and transgressive/ regressive cyclic deposition of an alternating series of fluvio-deltaic clastics and chalk/marl intervals (Spooner, 1935; Salvador, 1991).

The Cenozoic sequence (Fig. 2) crops out in the study area. High rates of deposition continued during Paleocene and Eocene (65 to 35 Ma)(Onellion, 1956; Cushing et al., 1964; Hosman, 1996). Marine Midway Shale deposition during Paleocene was followed by the fluvio-deltaic Wilcox Fm. containing regionally significant coal beds. Maximum subsidence rates obtained during Wilcox time, providing accommodation space for coal deposition. The Middle Eocene Claiborne Group consists of an alternating proximal and distal deltaic sequence: Cane River Fm.; Sparta Sand; Cook Mountain Fm.; and Cockfield Fm. Marine conditions returned during Late Eocene with deposition of Jackson Fm. clay and calcareous sand (Wilbert, 1953).
All of these Cenozoic strata are cut by the SRFZ (Cox et al., 2000; Gardner, 2006). South of the study area, the Peripheral Salt basin fault system (Fig. 1) cuts the Cenozoic sequence and marks the up-dip limit of Jurassic salt and of a detachment sheet within the salt. This graben system has experienced repeated activity related to flow of salt from mid-Mesozoic through Eocene (Hosman, 1982).

Quaternary sediments in the study area include alluvium of the Saline and Arkansas rivers and their tributaries. Active floodplains are flanked by older Holocene terraces on rivers and major tributaries, and there are at least three Pleistocene terrace complexes (Deweyville, Prairie, and Intermediate Complex) on these rivers (Saucier and Fleetwood, 1970; Saucier and Smith, 1986; Saucier and Snead, 1989; Saucier, 1994). The Deweyville Terraces are Wisconsinan (35 to 12 Ka). The other terraces are pre-Wisconsinan, but their ages are poorly constrained. A veneer of Late Pleistocene eolian

silt (Peoria Loess) is discontinuously present in the eastern study area, and a thin mid-Holocene eolian silt may be present on some ridges (Follmer, 1996; Cox et al., 2000). Quaternary and ongoing uplift and ground tilting in the study area and vicinity are indicated by geodetic surveys (Meade, 1975; Officer and Drake, 1981; Calais et al., 2006) and geomorphology (Schumm et al., 1982; Burnett and Schumm, 1983; Cox, 1994). These movements may be related to activity of the SRFZ along the northeast flank of the Monroe uplift.
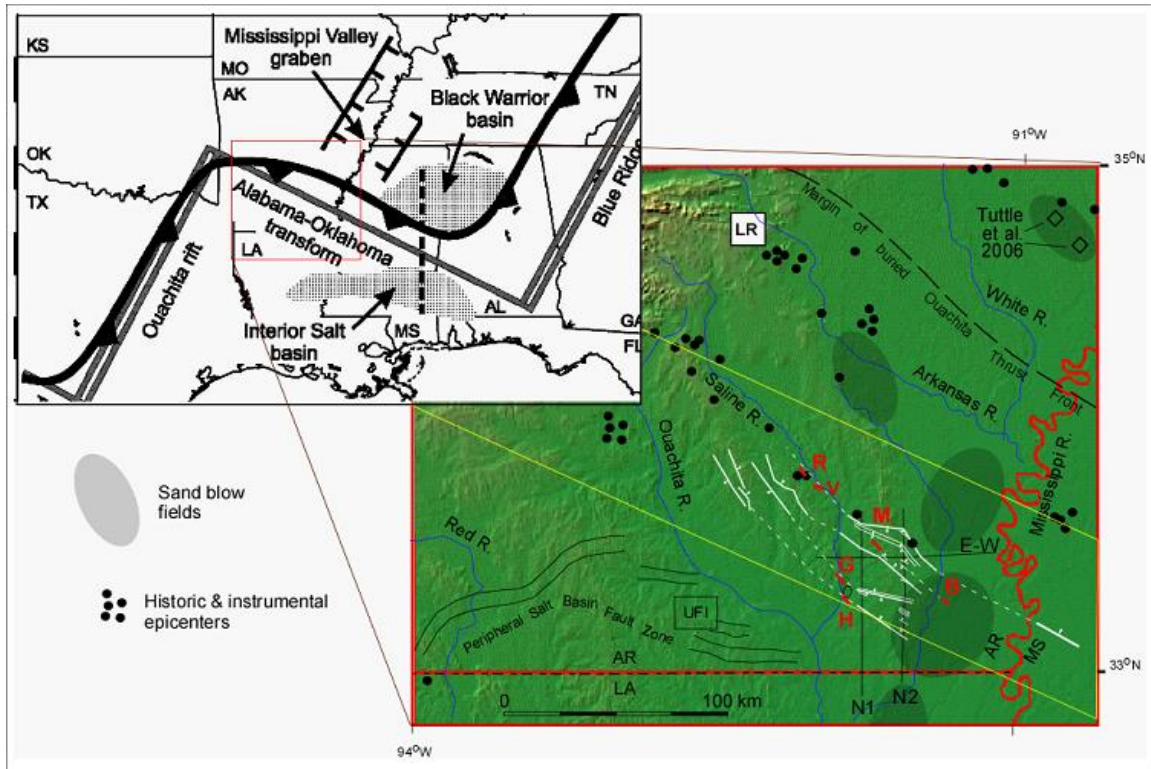

Figure 1. Study area (red box) along the Alabama-Oklahoma transform margin of Thomas (2006)(between yellow lines on the green shaded relief map). Regional black & white map shows tectonic setting (from Harry and Londono, 2004). Lines labeled N1, N2 and E-W denote locations of deep petroleum industry seismic profiles; White lines denote the mapped portion of the Saline River fault zone in the subsurface (ball on down-thrown fault block) identified on seismic profiles and from coal exploration bore-hole logs (faults dashed where speculative); Heavy red lines denote Quaternary faulting or folding identified in the field [B = Boydell, G = Gee's Landing, H = Horsehead Island, M = Monticello (not discussed herein, see Cox et al., 2000), R = Rison, and V = Vince Bluff]; Ellipses denote sand blow fields related to Holocene seismogenic faulting; Black dots denote historic earthquake epicenters (UFI = swarm induced by fluid injection). LR= Little Rock.

PREVIOUS INVESTIGATIONS

Cox et al. (2000) previously documented paleoseismicity on the SRFZ in Monticello, Arkansas (Fig. 1) by excavating six surface faults within the SRFZ: all faults displace marine Eocene units and fluvial Pleistocene units; five show post-Wisconsin loess movement (luminescence age = 23,600±3000 yr B.P.); and three deform middle to late Holocene silt (luminescence age = 5100±600 yr B.P.) as fault-tip flexures. A silt

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with a luminescence age of 3600±500 yr B.P. postdates deformation at this site. Trenches and road-cut exposures revealed 30 meters of left-lateral strike-slip offset along the principal SRFZ shear plane since Wisconsinan loess deposition, indicating an average slip rate of 1.13 to 1.46 mm/y.

Our trenching of sand blows at five sites along this fault zone revealed stratigraphic and cross-cutting relationships that show at least three sand-venting earthquakes of magnitude 6+ in the last 7000 years (Cox et al., 2004a; 2007). The USGS CPT (Cone Penetration Test) truck collected data to a depth of 20 m in sand blow fields along the SRFZ. The CPT measures cone tip resistance and sleeve friction on a cylinder driven into the ground. In addition, shear-wave velocities were measured at 2-m depth intervals. Together, the CPT data and the shear-wave velocities indicate that ground accelerations > 0.5 g are needed to liquefy susceptible sediments and vent them to the surface through surficial clay that is >5 m thick directly above the SRFZ. These accelerations suggest near source shaking and an earthquake of magnitude 7+ (Cox et al, 2007).

STUDY AREA

The study area in southeast Arkansas (Fig. 1) is characterized by moderate historic seismicity (≤M4.5) and a strong signature of active tilt-block tectonics throughout the Quaternary (Schumm et al., 1982; Burnett and Schumm, 1983; Cox, 1994). Although current configuration of regional seismic networks does not permit delineation of spatial patterns of microseismicity, alignments and clusters of felt earthquakes follow the Alabama-Oklahoma Transform deep-crustal discontinuity.

The Cenozoic substrate of the study area is unconsolidated, and readily-identifiable tectonic landforms do not survive more than a few millennia in the humid climate. Recognition of tectonic landforms is especially difficult in the dissected Tertiary uplands. Surficial faulting at upland trenching site on the SRFZ on Monticello Ridge (Cox et al., 2000) was only located serendipitously due to the excavation of new highway roadcuts. However, there are numerous linear scarps and river reaches on Wisconsinan and Holocene terraces and floodplains within the study area that may be late Quaternary tectonic landforms.

Information on the subsurface structure of the study area is limited because petroleum exploration seismic surveys have not been published and the area is north of petroleum production, so deep well log control is sparse. Consequently, faults have not been described adequately in the literature, although several fault-related anticlines have been the target of wildcat drilling in the study area. Fortunately, two N-S and one E-W petroleum exploration deep seismic reflection profiles could be obtained for this study from Seismic Exchange Inc. for academic use. These profiles reveal the northwest-striking Triassic rift system related to the Alabama-Oklahoma Transform (Fig. 1). Approximately 0.6 km of Triassic Eagle Mills was penetrated by Texaco Georgia Pacific #1 and 0.9 km of Triassic was penetrated by Amoco Edith Mehrens #1 in the center of the northern graben near profiles N1 and N2, respectively on Figure 1. Some faults show post-Triassic reactivation with flower structure geometries having both positive and negative elements and up-dip changes in sense of separation, suggesting a strong strike-slip component. Some reactivated faults cut Cenozoic section.

There are no reflection profiles for the northwest part of this rift zone, but a dense coverage of shallow (≤100 m deep) coal-exploration logs was obtained for that area of

this study from the North American Coal Company for academic use, and these logs reveal a series of horsts and grabens in Eocene sediments (Gardner, 2006) that show similar structure to the deeper rift zone mapped to the southeast (Fig. 1). The SRFZ is comprised of two northwest-striking parallel grabens and an intervening horst in the Mesozoic section. The northern graben is larger and contains up to a kilometer thickness of Triassic and Lower Jurassic sediment fill. In the western study area, grabens have been structurally inverted into horsts in the Eocene section (Gardner, 2006).

The Monroe uplift is a regional structural dome immediately to the south of the SRFZ. Uplift of this dome was greatest in Late Cretaceous, but Schumm et al. (1982) and Burnett and Schumm (1983) cite changes in stream sinuosities and progressive terrace deformations in northeast Louisiana and conclude that reactivation of the Monroe uplift has influenced stream courses during Quaternary and that uplift is ongoing. Since the northeast flank of the Monroe uplift is the SRFZ/Alabama-Oklahoma Transform, Schumm and Burnett may have actually detected fluvial responses to activity on this basement fault to the north.

ERA	SYSTEM	SERIES	GROUP/ FORMATION	Ma
CENOZOIC	QUATERNARY	HOLOCENE	FLOODPLAIN TERRACES	0.01
		PLEISTOCENE	PEORIA LOESS / DEWEYVILLE TERRACE / PRAIRIE TERRACE / INTERMEDIATE COMPLEX	2.4
	TERTIARY	PLIOCENE	UPLAND COMPLEX	5 / 35
		EOCENE	JACKSON FM. RISON CLAY / MOODY'S BRANCH MARL / CLAIBORNE GROUP / COCKFIELD FM. / COOK MOUNTAIN FM / SPARTA SAND / CANE RIVER FM.	55
		PALEOCENE	WILCOX FM. / MIDWAY SHALE	55 / 65

Figure 2. Stratigraphic chart for units that crop out or are near the surface in the study area. Dashed horizontal line denotes a significant unconformity.

INVESTIGATIONS UNDERTAKEN

Five sites were investigated in south Arkansas: Horsehead Island, Gee's Landing, Rison, Vince Bluff, and Boydell. These sites were selected based on: 1) indication of surface or near surface deformation; and 2) the presence of Holocene alluvium for dating of recent fault movements.

Horsehead Island and Gee's Landing are in the southern graben of the SRFZ, and Rison, Vince Bluff, and Boydell are in the northern graben. This work continued the methodologies used in previous investigations of Quaternary faulting (e.g., Cox et al., 2000, 2004a, 2007). Sites were excavated based on shallow subsurface data and

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geomorphic indications of faulting, logged on a 1.0 m grid, and photographed. Samples were collected for ^{14}C and optically stimulated luminescence (OSL) age dating.

RESULTS

<u>Horsehead Island</u> (33.3461°N, 91.9863°W)

This site is a riverbank excavation of deformation related to a surface rupture along the southern margin of the southern graben on N1 reflection profile (Fig. 1). According to area residents, "Horsehead" describes the map pattern the Saline River makes where it turns nearly 180° to begin a 4.5 km linear reach (Figs. 3 and 4). The abandoned channel pre-dating the linear reach of the modern river is highly sinuous ("older paleochannels" on Fig. 4). The modern channel is abruptly constricted at the upstream end of this bend, and this is interpreted to be where the river recently breached a fault scarp. The river was diverted 2 km northwestward along this scarp, flowing around it via a 180° "hairpin" bend. The river breached the scarp twice, leaving two hairpin abandoned channels ("young paleochannels" on Fig. 4) and the modern Horsehead bend.
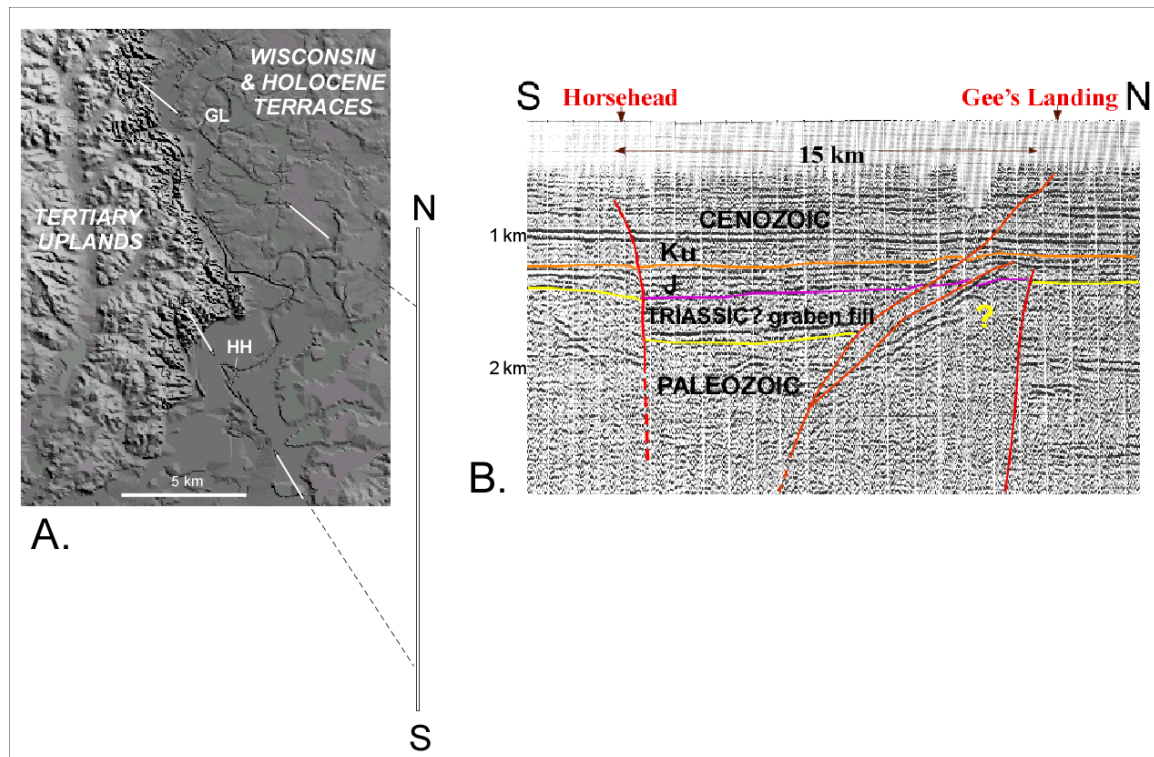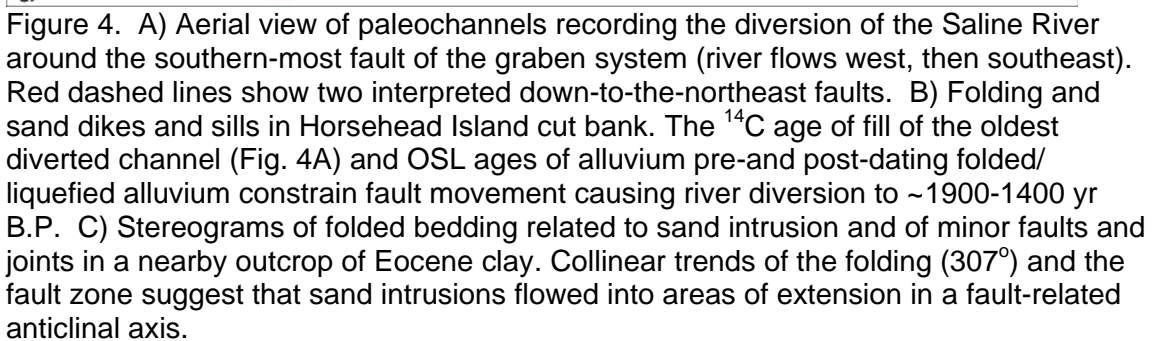

Figure 3. A) Shaded digital elevation model showing lineaments across of a portion of the southern graben of the Saline River fault system. HH = Horsehead site; GL = Gee's Landing site. B) A portion of the petroleum industry seismic reflection profile N1 across the southern graben of the Saline River fault zone along line N-S in Figure 3A. Note locations of Horsehead Island and Gee's Landing sites. Red lines are interpreted faults.
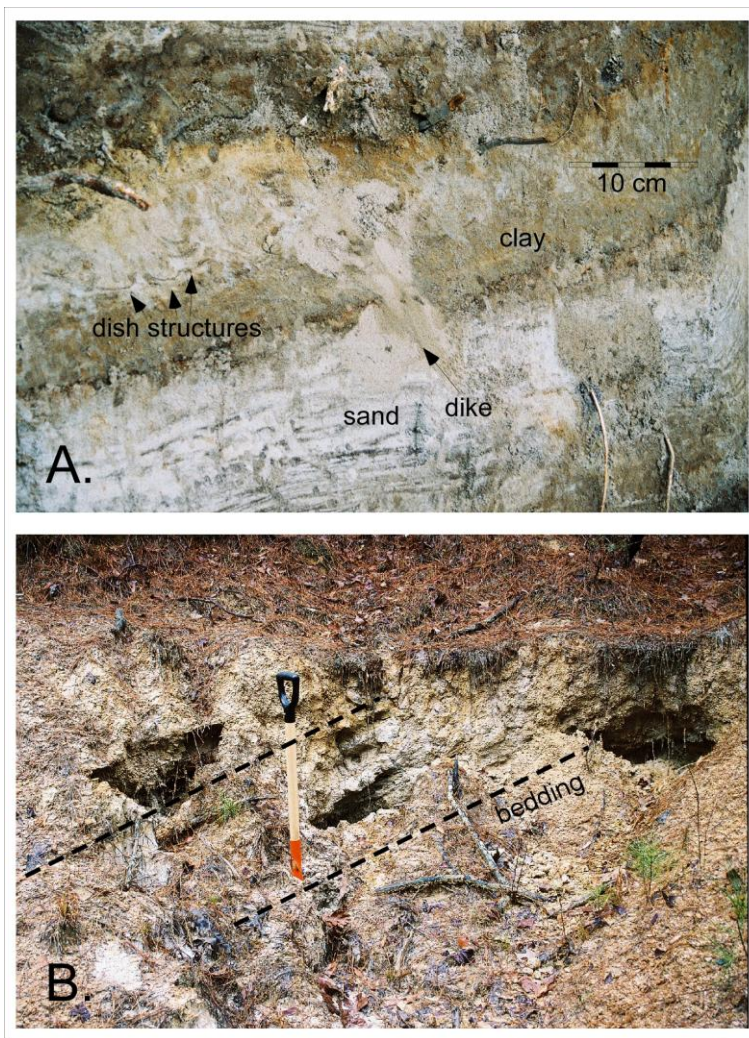
Figure 4. A) Aerial view of paleochannels recording the diversion of the Saline River around the southern-most fault of the graben system (river flows west, then southeast). Red dashed lines show two interpreted down-to-the-northeast faults. B) Folding and sand dikes and sills in Horsehead Island cut bank. The ^{14}C age of fill of the oldest diverted channel (Fig. 4A) and OSL ages of alluvium pre-and post-dating folded/ liquefied alluvium constrain fault movement causing river diversion to ~1900-1400 yr B.P. C) Stereograms of folded bedding related to sand intrusion and of minor faults and joints in a nearby outcrop of Eocene clay. Collinear trends of the folding (307°) and the fault zone suggest that sand intrusions flowed into areas of extension in a fault-related anticlinal axis.

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Figure 5. A) Small-scale liquefaction features at Horsehead Island. B) Eocene beds dipping northeast within the fault zone exposed in the uplands north of Horsehead Island.

At the channel constriction, alluvium is folded into an asymmetric anticline, and folded bedding strikes 307°, parallel to the SRFZ. Sand has been liquefied and strongly intruded as sills and dikes (Figs. 4 and 5), and the collinear trends of the folding and the fault zone suggest that sand intrusions flowed into areas of extension in the axis of a fault-related anticline.

Alluvium pre-dating the folding yields OSL ages of 1765+155 yr BP (UIC2467) and 1860+485 yr B.P. (UIC2466), and alluvium post-dating folding yields an OSL age of 1400+120 yr B.P. (UIC2469) (Table 1)(Fig. 4B). Organic-rich fill from a core (33.3604 °N, 91.9943°W) taken from the oldest abandoned "hairpin" channel (post-dating river diversion) yields a ^{14}C age of 1573-1406 yr B.P. (AA83179)(Table 2)(Fig. 4A). These age data constrain fault movement causing river diversion to ~1900-1400 yr B.P.

No Eocene "bedrock" is exposed in the riverbanks at Horsehead Island or Horsehead Bend. Downstream of Horsehead Bend along the southeast-trending linear

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reach of the river, Eocene silt, clay and coal beds are exposed only on the southwest bank. Therefore, two down-to-the-northeast faults are interpreted along the southwest margin of this graben, one at the valley constriction/river diversion and one following the linear reach. The true fault geometries may be complicated by local restraining and releasing bends due to a left-lateral slip component, such as seen in the northern graben (Cox et al., 2000).

Gee's Landing (33.4353°N, 91.9878°W)

 We cored and trenched a highly linear 2 m-high scarp at Gee's Landing following the surface projection of the northern fault of the southern graben on N1 reflection profile where it crosses the Saline River floodplain for 3.5 km (Figs. 3, 6, 7, and 8). A high water table due to prolonged flooding prevented us from trenching below two meters depth. Fortunately, the trench was logged before groundwater flow into the trench caused it to collapse.
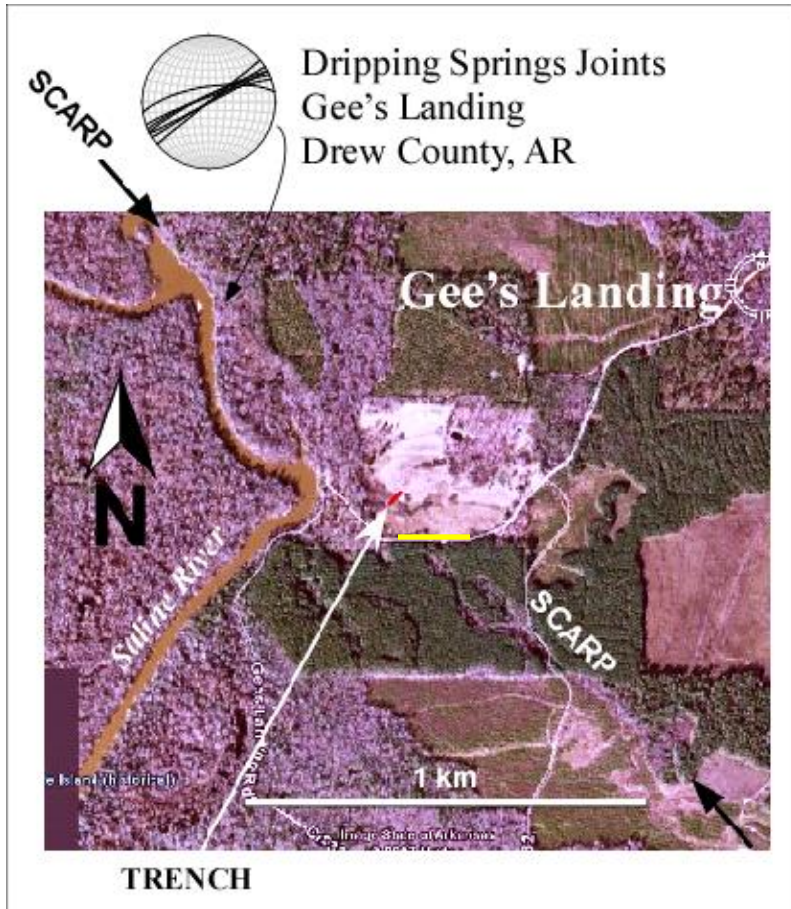
Figure 6. Scarp following the northern fault across the alluvial valley of the Saline River at Gee's landing. Yellow line denotes location of push-core transect (Fig. 7). Extension joints in Eocene strata exposed in the lower scarp are consistent with northeast-southwest compression of the modern stress field (Zoback, 1992).

 An alluvial sand at 2-m depth yields a ^{14}C age of 13,376-9088 yr B.P. (AA83842)(Table 2). We interpret this sand to be Late Wisconsinan Qtd3 Deweyville

terrace alluvium as mapped by Saucier and Smith (1986). Alluvium above this sand yields Holocene ages (AA87618, AA87619, AA87620, and AA87623, Table 2), and this upper alluvium is interpreted as both Qf1 and Qf2 Holocene floodplains of Saucier and Smith (1986) that onlap the Deweyville terrace surface.

Within Deweyville alluvium, a gleyed sand is truncated by a down-to-the-southwest fault at trench meter 5.7 (Fig. 8). The observed depth of this gleyed sand in the core transect constrains the fault tip displacement to be <1 m. Although not displaced in the trench, the Holocene/Pleistocene contact conforms to the topography of the scarp, consistent with the scarp being a tectonic warp above the fault. A fissure filled with organic sediment (14C ages ~1400 to 1290 yr B.P., AA87618, Table 2) extends upward from the fault to -1.3 m grid depth. The upper end of this fissure is interpreted to be the elevation of the floodplain surface at the time the fissure formed, and the age of its organic-rich fill is interpreted to record the date of fissuring.

At meter 7.3-8.4, tabular clastic dikes rooted in massive (liquefied) Pleistocene sand at the base of the trench connect to a sand intrusion that underlies brecciated soil and a surficial trough following the scarp face. This trough is filled with organic-rich sediment that yields a ^{14}C age of ~1185 to 1053 yr B.P. (AA87620, Table 2). Numerous other subvertical features cross-cut Holocene clay and soil horizons in the trench. Many of these features are cylindrical and are likely root casts or filled burrows, but several are tabular and branch upward (characteristic of clastic dikes).
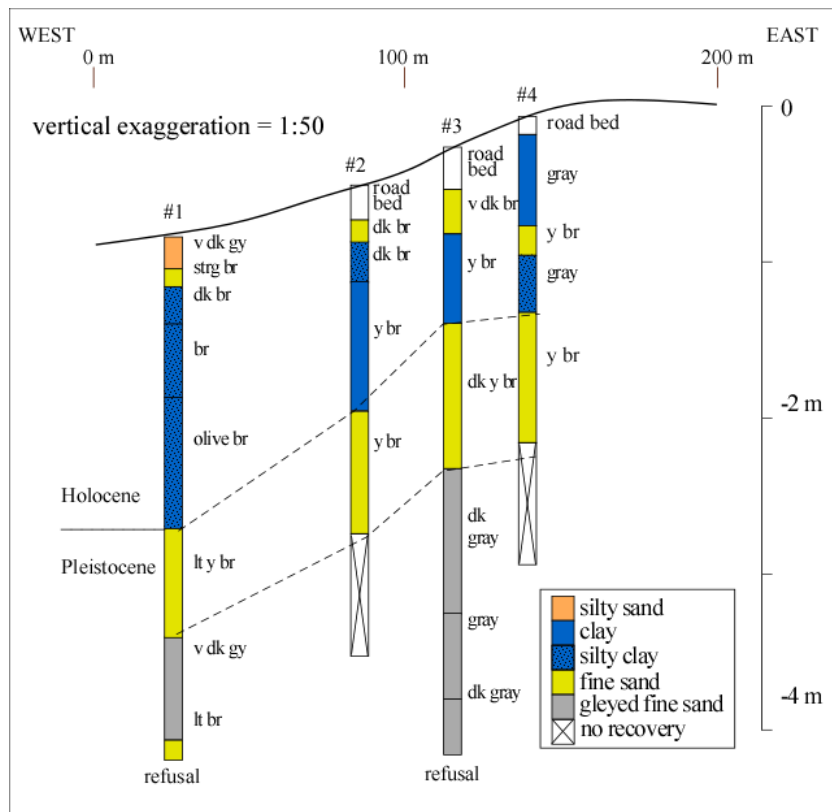

Figure 7. Push-core transect across scarp at Gee's Landing along an east-west county road 120 m southeast of trench site.

Three events are suggested in the trench log. The earliest event that displaced the gleyed Pleistocene sand post-dates ~13,400 yr B.P. but pre-dates the Holocene alluvium circa 9006-7657 yr B.P. The next event is minor, causing fissuring circa 1400-1300 yr B.P. The last event warped the surface, creating the modern 2 m high scarp and causing more extensive fissuring and sand venting along the scarp face circa 1200-1050 yr B.P.
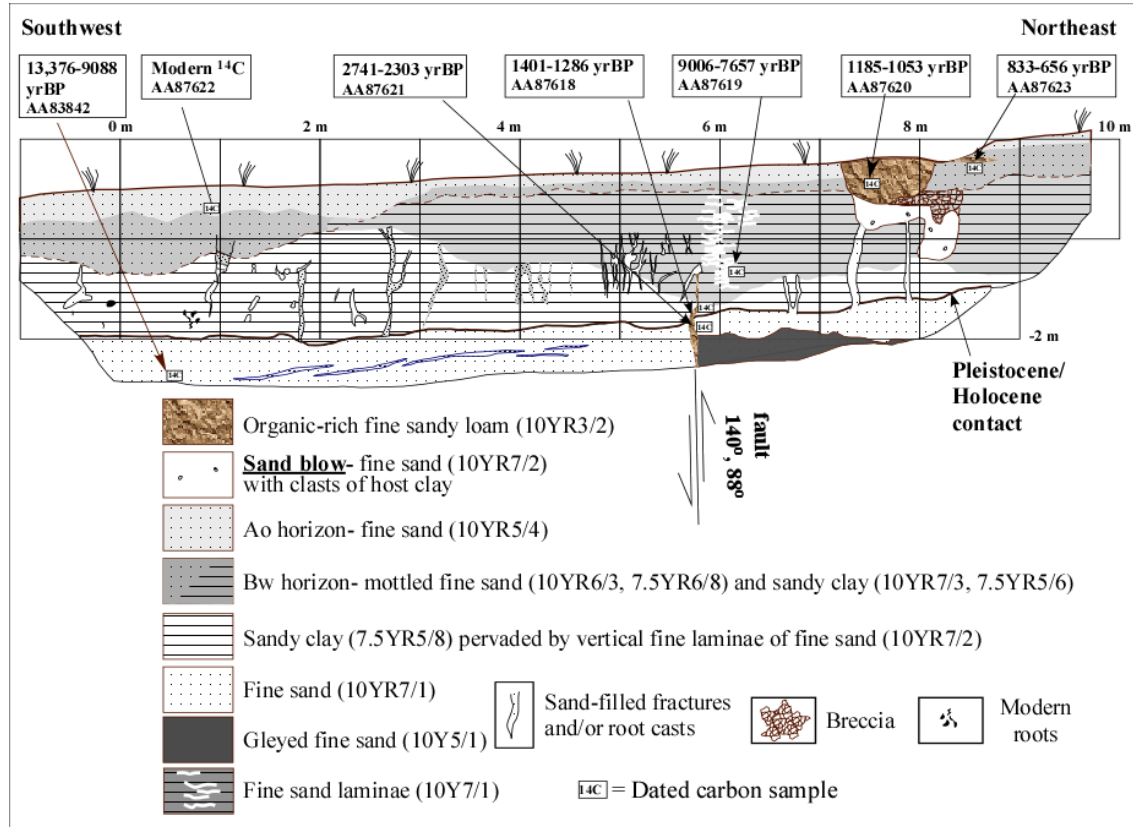

Figure 8. Log of Gee's Landing trench showing fault within late Wisconsinan alluvium and vented sand hosted in Holocene alluvium. [14]C ages shown in boxes (see Table 2).
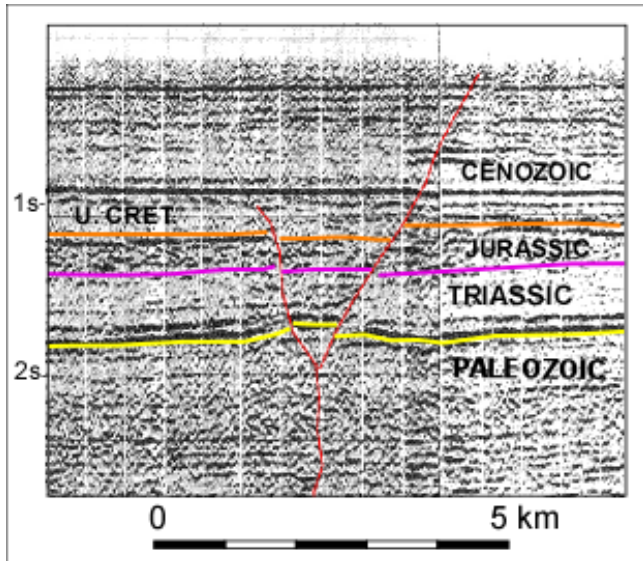
Figure 9. A portion of Petroleum seismic reflection profile N2 (Fig. 1) showing a strike-slip flower structure in the center of the northern graben of the Saline River fault zone along strike of surface faulting at Monticello, Arkansas (Cox et al., 2000), and at the Rison, Vince Bluff and Boydell sites discussed herein. Red lines denote interpreted faults. This flower structure indicates Cenozoic strike-slip reactivation of the Triassic graben system.

Rison site (33.8619^{o}N, 92.1729^{o}W)

This site is 70 km along strike from petroleum industry reflection profile N2 showing a SRFZ flower structure indicating strike-slip faulting (Fig. 9) and 50 km northwest along strike of the SRFZ from the Monticello trench study of Cox et al. (2000)(Fig. 1). A faulted anticline was excavated in a cut bank where the Saline River breaches a linear scarp on its alluvial valley (Fig. 10). The fault is a near vertical 1.5 m-wide zone of massive sand that strikes 326° and displaces (post-dates) organic-rich alluvial horizons that yield ^{14}C ages of 790-550 yr B.P.   We interpret the anticline as a fault-propagation fold, and it is topographically expressed as a prominent highly-linear scarp that displaces Holocene and Late Wisconsinan Deweyville alluvial terraces. The Holocene floodplain is displaced ~1 m down-to-the southwest along the southeast portion of the scarp, and the scarp is steep and up to 3 m high on the northwest portion where it separates Holocene floodplain and a Deweyville terrace surface. Elevation of the Caney Point marl/Rison clay contact in coal exploration hole logs reveal > 80 m down-to-the-southwest displacement of Eocene "bedrock" across the fault at Rison (Fig. 11).
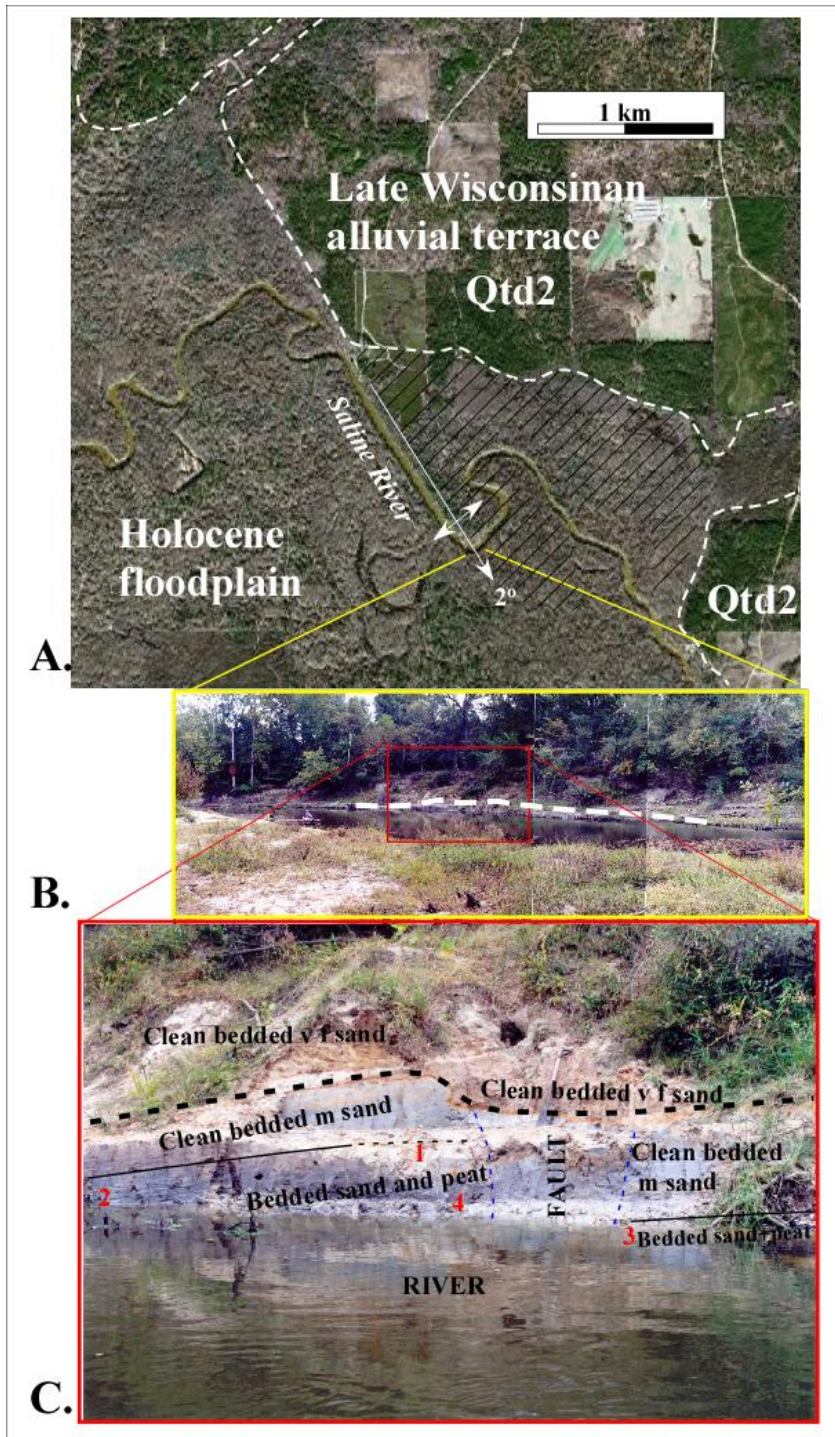
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Figure 10. A) Aerial view of scarp and anticline in the Saline River alluvial valley near Rison, Arkansas. Cross-hatched area of flood plain has been uplifted ~1 m. B) View of the river breach of the anticline looking southeast. Dashed white line denotes an alluvial contact that rises and falls with the topographic expression of the anticline. C) Excavation of fault displacement of alluvial units in the axis of the anticline. Displacement is ~ 1 m (shovel for scale). Red numbers denote ^{14}C samples that yield the following ages: 1) 720 to 550 yr B.P. (Beta162557); 2) 727-628 yr B.P. and 602-558 yr B.P. (AA87878); 3) 793-678 yr B.P. (AA87880); and 4) 791-678 yr B.P. (AA87879).
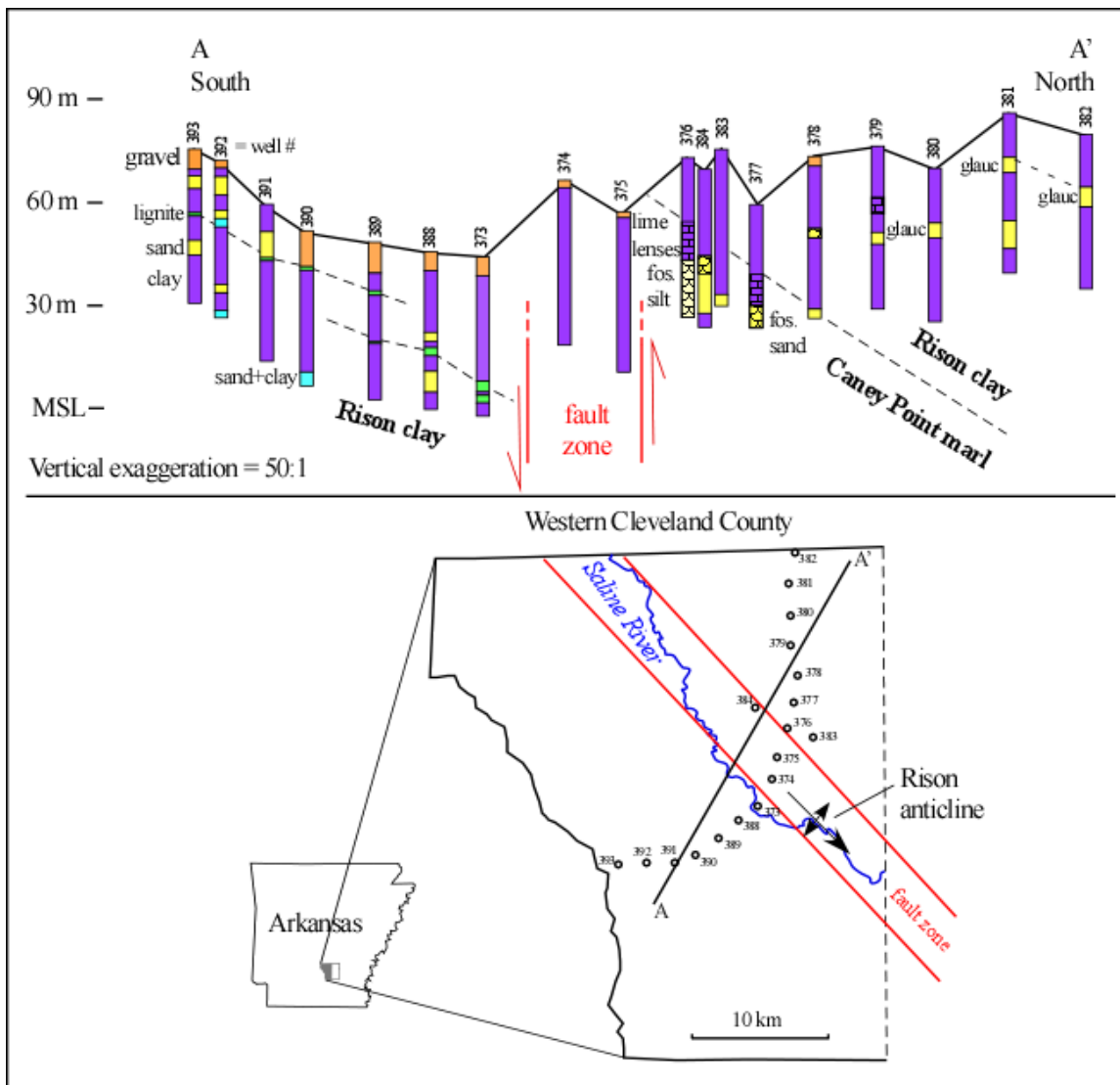
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Figure 11. Cross-section across the vicinity of the Rison anticline/fault scarp constructed using coal exploration hole logs in Cleveland County, Arkansas (Holbrook, 1980).

Vince Bluff site (33.7712°N, 92.0642°W)

        This site is 13 km southeast of the Rison site along strike of the SRFZ. An anticline (284°, 3°) in older alluvium (inter-bedded sand and peat overlying vein-quartz gravel) is exposed in the northwest riverbank at Vince Bluff (Fig. 12). Beds in surficial fine sand alluvium are not folded. The axis is covered by a slump and colluvium, and the opposite bank is covered by colluvium. A folded peat horizon yields ^{14}C ages of 5893-5804 yr B.P. and 5775-5642 yr B.P. There is no scarp or lineament associated with this anticline, and thus it is interpreted to be a mid-Holocene structure (~5000 years old) for which the topographic expression has been removed by river migration and sedimentation. Although the valley in the vicinity of this anticline is mapped as Holocene floodplain (Saucier and Smith, 1986), the floodplain shows a local large amplitude meander scroll pattern characteristic of Wisconsinan Deweyville terraces.

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This pattern suggest that a portion of Deweyville terrace level Qtd4 (typically buried by a veneer of Holocene alluvium) has been uplifted and exhumed.
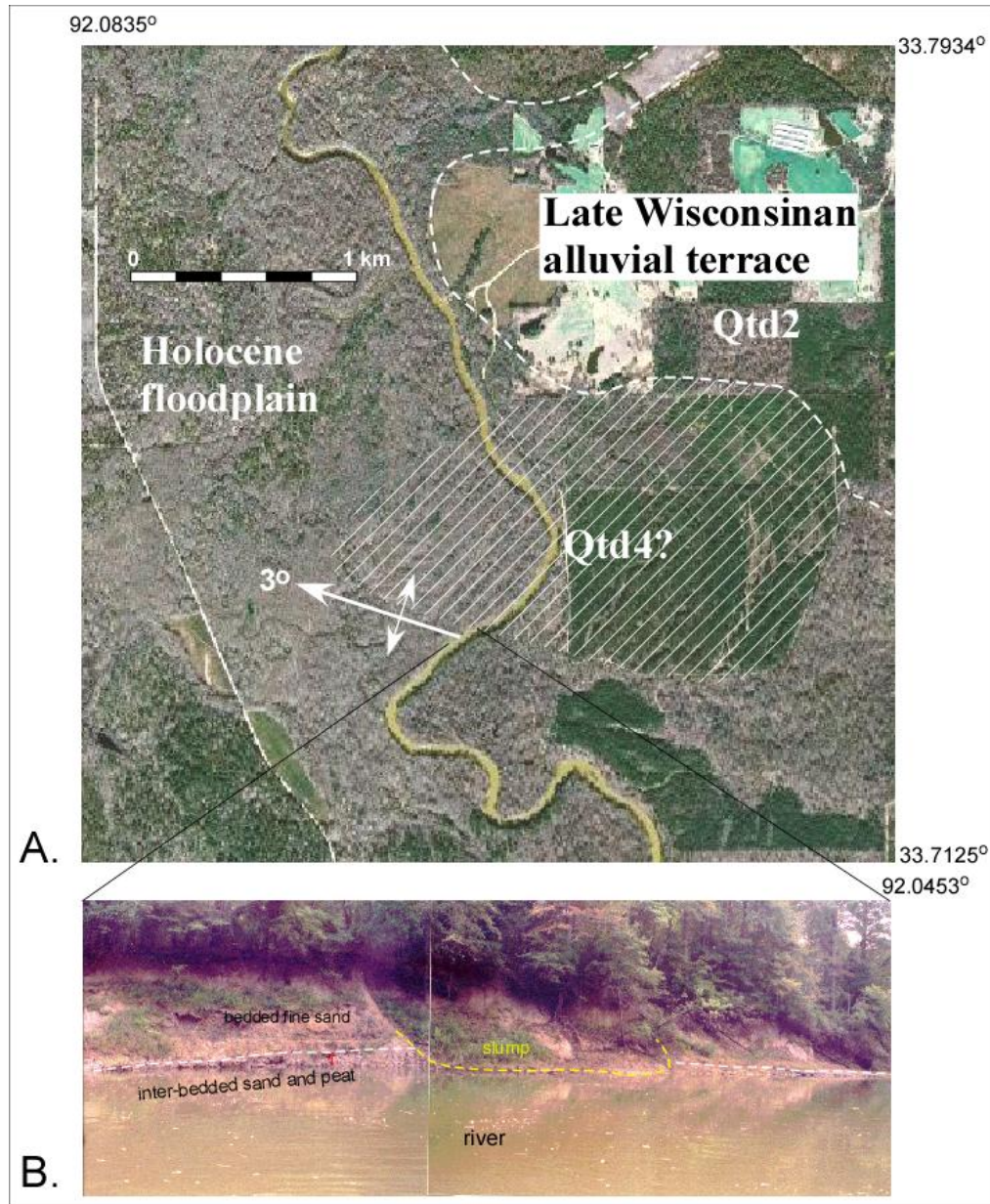

Figure 12. A) Aerial view of Vince Bluff vicinity showing location of anticline. Cross-hatching denotes a large amplitude meander scroll pattern characteristic of Wisconsinan Deweyville terraces. B) View looking northwest at river bank exposure of anticline. Dashed white line denotes top of folded alluvial beds (overlying beds are horizontal). Red number "1" denote a ^{14}C sample that yields ages of 5893-5804 yr B.P. and 5775-5642 yr B.P. (AA87881, Table 2).

Boydell, AR (33.3439°N, 91.4750°W)

Surficial geology at this site is mapped as middle to late Holocene overbank alluvial silts and clays and crevasse splay sands (Saucier, 1994). This site is on the

northern margin of the Ashley County sand blow field (Cox et al., 2004, 2007) and targets a channel lineament (bearing 320°) along a mid-Holocene (~4500 to 6000 yr B.P.) abandoned meander belt of the Arkansas River (Ward's Bayou)(Fig. 13). A surficial scarp is not evident at this site, so two shallow S-wave seismic reflection profiles were collected by Dr. James Harris (not included herein) and an electrical conductivity survey was conducted to precisely site the trench. The shallow S-wave profiles are parallel and overlapping, permitting determination of a strike of 290° on a prominent fault plane (Cox et al., 2004b). The S-wave profiles reveal multiple upward-diverging faults consistent with the top of a transpressive flower structure that cuts Eocene and Quaternary units to
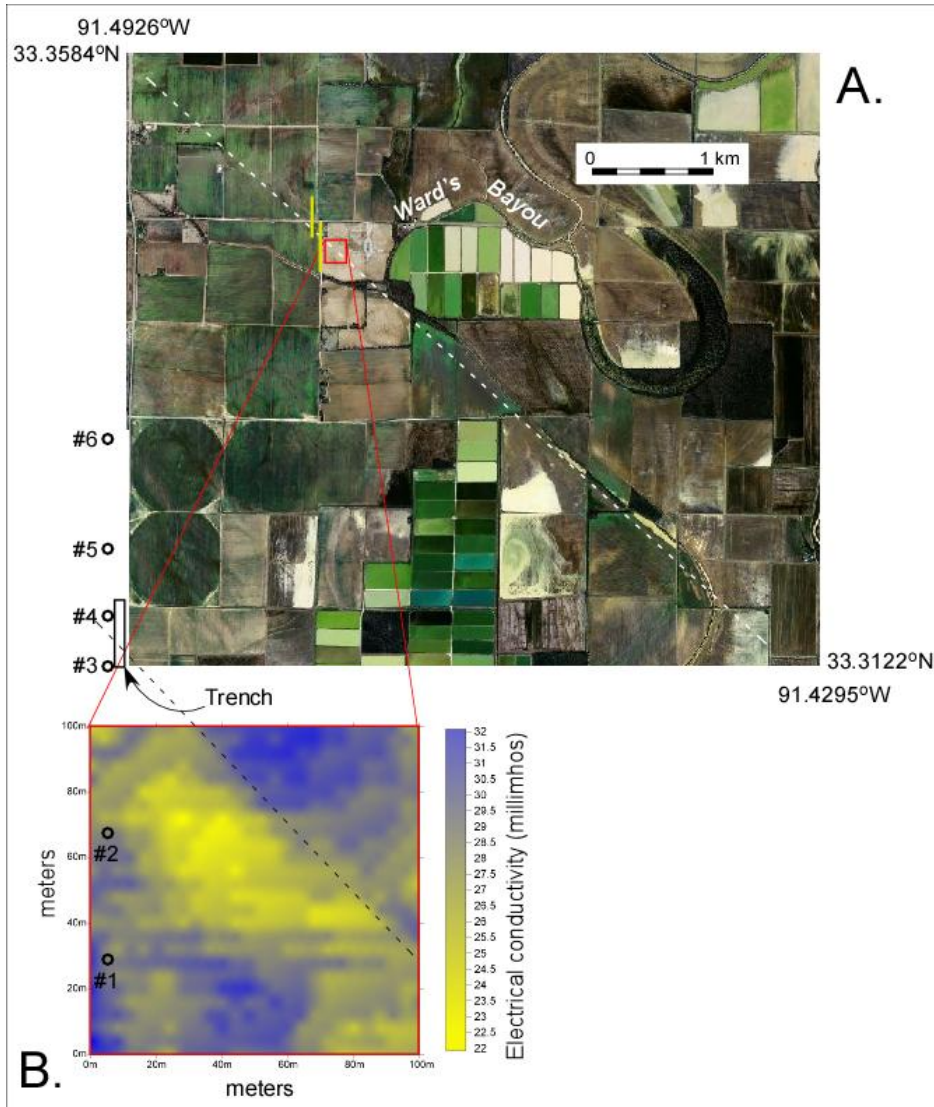

Figure 13. A) Aerial view of Boydell site showing lineament (denoted by dashed white line) following a straight reach of an Arkansas River paleochannel. Yellow lines denote location of shallow s-wave seismic reflection profiles previously collected. B) Electrical conductivity map showing steep gradient indicating sand against clay along the lineament. Numbered circles denote core holes on Figure 14, and their positions are shown relative to the conductivity map. Rectangle shows location of trench (Fig. 15).
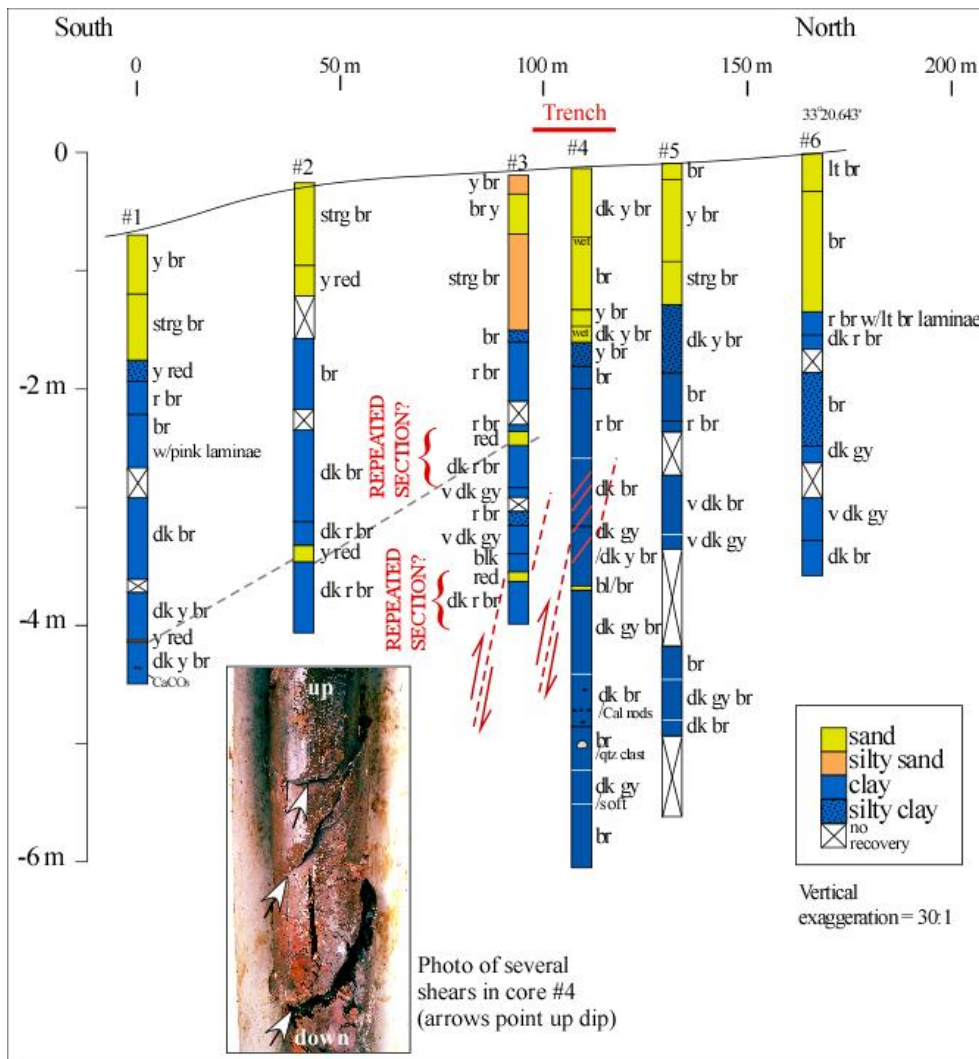
Figure14. Push-core transect across lineament at Boydell site.

within 20 m or less of the surface. A steep linear gradient from low to high conductivity suggests a sharp sand-against-clay contact <6 m deep parallel to the northwest fault strike identified from the overlap of the seismic profiles (Fig. 13).

A transect of push cores was collected across the interpreted shallow fault (Fig. 14), and several suggestions of faulting were found below 2 m depth: 1) repeated section with a red sand marker bed in core #3 suggesting reverse faulting; 2) shearing in core #4 with dip-slip micro-mullion (shears are not interpreted as shrink-swell features because they were observed only in a 60 cm length of core #4); and 3) below 3 m depth, clays are oxidized (red) in cores south of the interpreted fault(s) and gleyed (gray) to the north, suggesting a water barrier.

A 20-m long, 2-m deep trench was excavated along the push-core transect above core #4 (Fig. 15). A high water table prevented deepening the trench, and water seepage caused substantial collapse of the trench within a week. No faults were observed in the trench. However, many vertical sand bodies in this trench may be seismically-induced sand dikes that cut the underlying clay during liquefaction and venting of a deeper sand and pinched out through the clay interval after water pressure decayed. Sand dikes that

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severely constrict or pinch out through clay beds are observed at other trenching sites in the Ashley County and Desha County sand blow fields (Cox et al., 2004b, 2007).
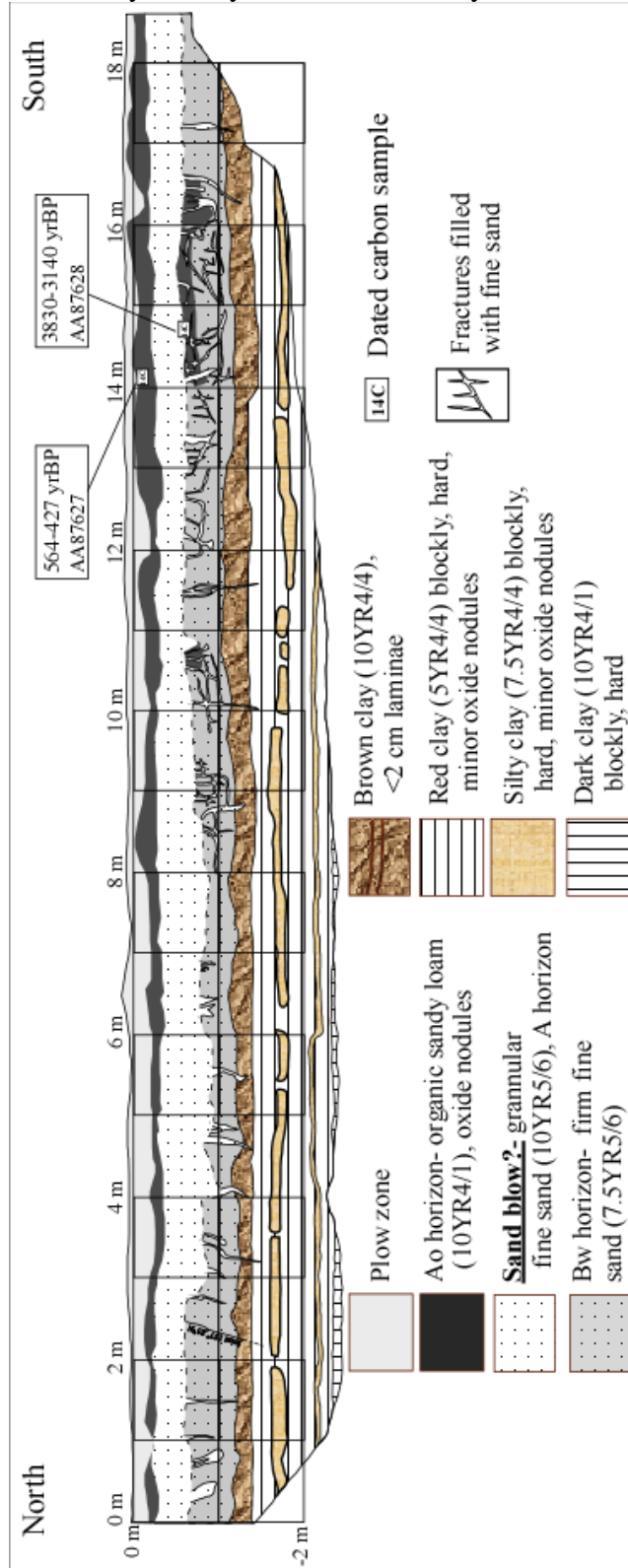

Figure 15. Log of trench at Boydell site.

Furthermore, a granular brown fine sand above the Bw soil horizon at the Boydell site is interpreted as vented sand from these dikes. This interpretation is consistent with observed upward termination of the dikes at the grannular brown sand (blow) and with the similarity in composition, texture and color of this sand to that in the dikes. This sand blow postdates a buried Ao soil horizon circa 3830-3140 yr B.P. A coincidence of abundant sand dikes, a 20 cm drop in elevation of sub-blow alluvial strata, and local preservation of the buried Ao soil horizon between meters 12 and 17 in the trench shows subsidence and fracturing centered in that area and suggests a large vent of the blow is near this part of the trench.

A silty clay bed at ~1.7 to 1.8 meter depth in the trench shows north-south extension by boudinage (Fig. 15). The necks between the boudins are filled with red clay from both above and below the silty clay bed. Strata above the upper red clay show no obvious extensional features, and sand-filled fractures above the upper red clay have no preferred orientation and cannot be related to north-south extension. Extension of the silty clay is interpreted to have occurred before deposition of the alluvium and vented sand above the red clay. Spreading was probably driven by lateral spreading and flow of the red clay toward a creek 300 m to the south. The surface slopes $<0.2^{o}$ and should not fail by sliding in the absence of ground shaking (Valsamis et al., 2010).

The 3830-3140 yr B.P. age of the buried Ao soil horizon below the sand blow deposit is consistent with a 4500 to 6000 yr B.P. mid-Holocene age estimated by Saucier (1994) for this terrace and the associated meander belt of the Arkansas River. The most recent surface rupture on the fault(s) interpreted below the trench pre-dates the buried Ao soil horizon and probably is coeval with establishment of the straight river reach on the paleo-Arkansas River circa 5000 yr B.P.

SUMMARY AND CONCLUSIONS

Figure 16 shows reinterpretation of SRFZ considering these new data herein. This study shows that the Saline River was diverted 2 km to the northwest circa 1900-1400 yr B.P. by a down-to-the-northeast surface fault rupture at Horsehead bend along the southern margin of the SRFZ's southern graben. On the northern fault of this same graben, a trench across a linear scarp following a down-to-the-southwest fault at Gee's Landing revealed three paleoearthquakes at 13,400-7700 yr B.P., 1400-1300 yr B.P., and 1200-1050 yr B.P. Sand blows are visible on a cleared acreage on the Saline River floodplain between Horsehead Island and Gee's Landing, but they have not been excavated.

Within the SRFZ's northern graben, a prominent linear scarp follows a down-to-the-southwest fault and related anticline near Rison that post-dates alluvium that yields ^{14}C ages of 790-550 yr B.P. At Vince Bluff, thirteen kilometers along strike of the SRFZ to the southeast of the Rison anticline, another anticline with no topographic scarp folds alluvium that yields ^{14}C ages of 5893-5804 yr B.P. and 5775-5642 yr B.P. Seventy kilometers farther along strike of the SRFZ to the southeast (beyond the Monticello trench sites of Cox et al., 2000), a trench in Mid/Late Holocene alluvium (~6000-3000 yr B.P.) at Boydell revealed no faulting within 2 m of the surface, although shallow geophysics and coring indicate near surface faults at this site. It should be emphasized that only the most prominent lineaments have been investigated to date, and numerous

other areas with geomorphic suggestions of faulting have not been investigated. Many have been reconnoitered and a significant number warrant excavation.

Although highly speculative, data reported herein permit a 70-km rupture from Vince Bluff to Boydell circa 5000 yr B.P. on the northern graben flower structure. Sand blow events loosely constrained to mid-Holocene in the Ashley and Desha County sand blow fields (Cox et al., 2004a, 2007) may record such a surface rupture. Furthermore, at one site in the Ashley County sand blow field near Boydell, 40 km southeast of the Cox et al. (2000) Monticello fault trenching sites and 90 km southeast of the fault exposure near Rison, ^{14}C dating of organic material filling a vent crater indicates the most recent sand venting episode was ~700 yr B.P. (Cox et al., 2004a), similar in age to the faulting event near Rison. Due to the growing recognition of the common occurrence of remote triggering of one earthquake by another, these events cannot be assumed to be related to a single fault rupture. Indeed, the age of one faulting event at Gee's Landing is compatible with the age of faulting at Horsehead bend, but these sites are on different faults. Much more data is required to correlate faulting and liquefaction events along the SRFZ.
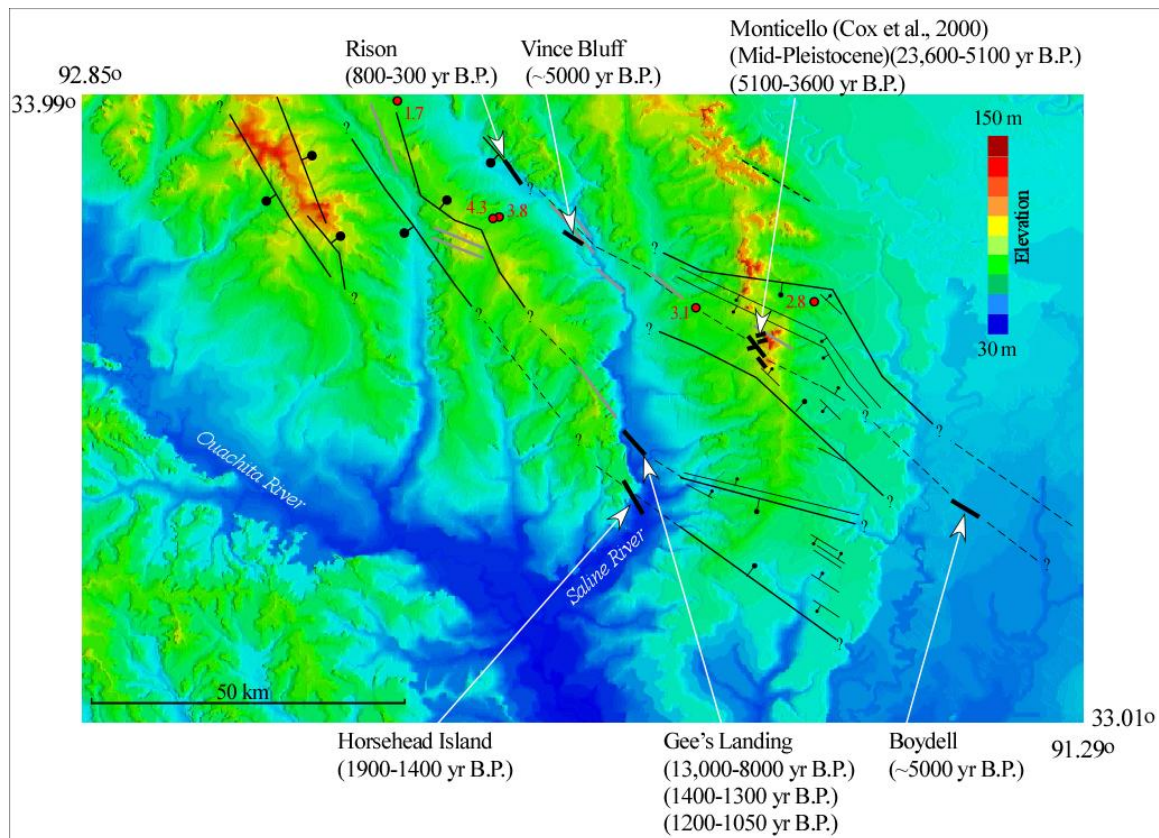

Figure 16. Summary DEM map showing locations of investigation sites along the Saline River fault system and ages of Quaternary faulting at these sites. Heavy lines denote Quaternary faulting or folding identified in the field. Other black lines denote the mapped portion of the Saline River fault zone in the subsurface (ball on down-thrown fault block) identified on seismic profiles and from coal exploration bore-hole logs (faults dashed where speculated). Gray lines denote topographic lineaments of possible fault origin. Red dots denote historic earthquake epicenters with magnitudes.

Cox et al. (2000) document a strong left slip component on the SRFZ, expected in the modern northeast-southwest compressional stress field of the mid-continent. Indeed, Holocene deformation at sites described herein within the northern graben of the SRFZ show compressional and transpressional structural styles including revere faulting and related folding and flower structure geometries. However, Holocene faulting at Horsehead bend and Gee's Landing indicates the southern graben is reactivating in extension or transtension. It is unfortunate that the detailed geometry of the fault system is not known in the immediate vicinity of these two sites, but that allows speculation that an unknown complication in the geometry of the graben is creating a releasing bend. Interestingly, the northwestern horsts and grabens of the SRFZ mapped with shallow coal exploration data ($<$100 m depth) show Eocene and post-Eocene structural inversion (Gardner, 2006), confirming that compression dominates the fault system. Our understanding of the SRFZ would benefit most from additional seismic reflection data.

TABLE 1. Results of Optically stimulated luminescence (OSL) ages on quartz grains for fluvial sediments.

Site	Lab No.[a]	Equivalent Dose (Gy)[b]	U (ppm)[c]	Th (ppm)[c]	K (%)[c]	Cosmic dose (mGrays/yr)[d]	Dose Rate (Gy/ky)	IRSL age $\pm$ 1σ (yrs)
Horse-head	UIC2466	1.91 ± 0.48	0.9 ± 0.1	2.2 ± 0.1	0.64 ± 0.01	0.16 ± 0.02	1.02 ± 0.05	1860 ± 485[e]
"	UIC2467	1.91 ± 0.03	0.9 ± 0.1	2.3 ± 0.1	0.69 ± 0.01	0.17 ± 0.02	1.08 ± 0.05	1765 ± 115[e]
"	UIC2469	0.61 ± 0.02	0.3 ± 0.1	0.7 ± 0.1	0.20 ± 0.01	0.17 ± 0.02	0.44 ± 0.02	1400 ± 120[e]

[a]All analyses were conducted at the Luminescence Dating Research Laboratory, Department of Earth and Environmental Sciences, University of Illinois at Chicago (UIC). See Figure 4 for sampling locations within the Horsehead Island excavation.
[b]150 to 250 μm quartz fraction analyzed under blue-light excitation (470 ± 20 nm) by single aliquot regeneration protocol (Murray and Wintle, 2003).
[c]U, Th and K20 content analyzed by inductively coupled plasma-mass spectrometry analyzed by Activation Laboratory LTD, Ontario, Canada.
[d]From Prescott and Hutton (1994).
[e]Ages calculated using a variant of the minimum age model of Galbraith et al. (1999).
[f] Ages calculated using the central age model of Galbraith et al. (1999).
All errors are at 1 sigma and ages from the reference year AD 2009.

TABLE 2. Results of ^{14}C analyses.

Site	Lab No.[a]	Sample Material	Technique	Radiocarbon age ± 1σ yr BP	$\frac{^{13}C}{^{12}C}$ °/$_{oo}$	Calibrated 2σ age yr B.P.[b] (Italics = minor peak area)
Horse-head	AA83179	Bulk soil	AMS	1614±40	-26.7	1573-1406
"	AA83181	Wood	AMS	170±39	-24.9	295-243 231-124 118-54 Modern
Gee's Landing	AA83842	Charcoal	AMS	9,850±880	-24.9	13,376-9088 *9050-9035*
"	AA87618	Charcoal	AMS	1,910±280	-31.2	*2691-2639* *2613-2598* 1401-1286
"	AA87619	Bulk soil	AMS	7,430±320	-25.1	9006-7657
"	AA87620	Charcoal	AMS	1,199±35	-27.6	1185-1053
"	AA87621	Charcoal	AMS	2,404±92	-30.1	2741-2303
"	AA87622	Bulk soil	AMS	Post-bomb	-24.9	Modern
"	AA87623	Bulk soil	AMS	803±68	-27.2	*908-843* 833-656
Rison	BETA 162557	Plant fragments	Standard	700 ± 60		720-550
"	AA87878	Plant fragments	AMS	702±47	-29.2	727-628 602-558
"	AA87879	Charcoal	AMS	820 ±36	-25.0	791-678
"	AA87880	Wood	AMS	825±35	-26.7	793-678
Vince Bluff	AA87881	Wood	AMS	4,995±51	-28.2	5893-5804 5775-5642
Boydell	AA87627	Bulk soil	AMS	475±61	-26.1	*641-589* 564-427 *390-389* *378-320*
"	AA87628	Bulk soil	AMS	3,230±140	-15.8	3830-3140

[a] AA denotes samples analyzed by The University of Arizona AMS facility, and BETA denotes BETA Analytic, Inc., Miami, Florida. See Figures 4, 8, 10, 12, and 15 for sampling locations within the trenches.

[b] Following Stuiver et al. (2005)

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NON-TECHNICAL SUMMARY

Several lines of evidence suggest there are active faults capable of generating moderately large earthquakes in southeast Arkansas. These lines of evidence include faults observed in geologically young sediments and deposits of sand that liquefied and erupted onto the surface during prehistoric earthquakes. This study investigated five additional sites of suspected young faulting in the region. Evidence was found for up to five additional prehistoric earthquakes.